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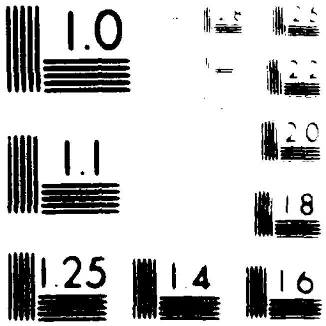
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TECHNICAL REPORT No. 52

Coherent States for the Damped Harmonic Oscillator

by

K. H. Yeon, C. I. Um and Thomas F. George

Prepared for Publication

in

Physical Review A

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

September 1987

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REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY 2b DECLASSIFICATION/DOWNGRADING SCHEDULE	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
4 PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/87/TR-52	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260	7b ADDRESS (City, State and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217
8a NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043
8c ADDRESS (City, State and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217	10 SOURCE OF FUNDING NOS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT NO

11 TITLE
Coherent States for the Damped Harmonic Oscillator

12 PERSONAL AUTHOR(S)
K. H. Yeon, C. I. Um and Thomas F. George

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Yr, Mo, Day)	15 PAGE COUNT
	FROM ____ TO ____		

16 SUPPLEMENTARY NOTATION
Prepared for publication in Physical Review A

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB GR	DAMPED HARMONIC OSCILLATOR COHERENT STATES CALDIROLA-KANAI HAMILTONIAN QUANTUM DISSIPATIVE SYSTEM

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Using the Caldirola-Kanai Hamiltonian for the damped harmonic oscillator, exact coherent states are constructed. These new coherent states satisfy the properties which coherent states should generally have.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☒ DTIC USERS ☐	21 ABSTRACT SECURITY CLASSIFICATION Unclassified

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE NUMBER (Include Area Code)	22c OFFICE SYMBOL
Dr. David L. Nelson	(202) 696-4410	

Physical Review A, in press

Coherent States for the Damped Harmonic Oscillator

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PACS Nos. 02.90,, 03.65 W, 05.30-d, 42.50. Bs

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Since the coherent states for the harmonic oscillator have been constructed first by Schrödinger,[1] they have been widely used to describe many fields of physics.[2)-5)] Recently Nieto and Simmons have constructed coherent states for particles in general potentials[6] and have applied their formalism to confining one dimensional systems:[7] harmonic oscillator with centripetal barrier and the symmetric Pöschl-Teller potential, and also to nonconfining one dimensional systems[8] with the symmetric Rosen-Morse potential and the Morse potential. For the time-dependent systems Lewis and Riesenfeld[9] have investigated the harmonic oscillator with time-dependent frequency $\omega(t)$. Hartley and Ray[10] has obtained exact coherent states for this time-dependent harmonic oscillator on the basis of Lewis and Riesenfeld theory. Hartley-Ray results satisfy most, but not all, of the properties of the coherent states. In the case of a quantum mechanical model of a damped forced harmonic oscillator, Dodonov and Man'ko[11] have introduced the Caldirola-Kanai Hamiltonian[12] with an external force term and constructed integrals of motion of this Hamiltonian, eigenstates and coherent states. The main flaw of the Dodonov-Man'ko result is its uncertainty relation $\Delta p \cdot \Delta x \geq e^{-\gamma t}\hbar/2$ in which the uncertainty vanishes as $t \to \infty$. This contradiction is critically reviewed by Greenberger[13], and Cervero and Villarroel.[14] Greenberger introduced the variable mass: $m = m_0 e^{\gamma t}$ and removed the violation of uncertainty.

In this paper we construct exact coherent states for the damped harmonic oscillator described by the Caldirola-Kanai Hamiltonian

$$\mathcal{H} = e^{-\gamma t}\,\frac{p^2}{2m} + e^{\gamma t}\,\frac{1}{2}\,m\,\omega_0^2\,x^2. \tag{1}$$

We first define the creation operator a^+ and annihilation operator a, and using these operators we will derive the representations of coherent states and investigate whether our coherent states satisfy the following properties of coherent states: (1) They are eigenstates of annihilation operator. (2) They are created from the vacuum or the ground states by an unitary operator. (3) They represent the minimum uncertainty states. (4) They are not orthogonal but complete and normalized.

In the preceeding paper[15] (hereafter referred to as paper I) we have developed the quantum theory of the damped driven harmonic oscillator with the Caldirola-Kanai Hamiltonian with an external driving force f(t) by path integral method. In paper I, setting f(t) = 0, the Hamiltonian is reduced to Eq. (1) and all other results become those corresponding to the Hamiltonian (Eq.(1)), and the Lagrangian, mechanical energy and propagator are given by

$$\mathcal{L} = e^{\gamma t}\left(\frac{1}{2}\, m\dot{x}^2 - \frac{1}{2}\, m\omega_0^2\, x^2\right), \tag{2}$$

$$E = e^{-2\gamma t}\,\frac{p^2}{2m} + \frac{1}{2}\, m\omega_0^2\, x^2, \tag{3}$$

$$K(x,t;\, x_0,\, 0) = \left(\frac{m\omega e^{\frac{\gamma}{2}t}}{2\pi i\hbar \sin\omega t}\right)^{\frac{1}{2}} \exp\Big[\frac{im}{4\hbar}\Big\{\gamma(x_0^2 - e^{\gamma t}\, x^2) + \frac{2\omega}{\sin\omega t}\Big((x^2 e^{\gamma t} + x_0^2)\cos\omega t - 2\, e^{\frac{\gamma}{2}t}\, x x_0\Big)\Big\}\Big], \tag{4}$$

with $\omega = (\omega_0^2 - \gamma^2/4)^{\frac{1}{2}}$. Here, the energy expression in Eq. (3) is not equal to the Hamiltonian itself. With the help of Eq. (4) and the wave function of simple harmonic oscillator, we obtain the wave function of the

damped harmonic oscillator:

$$\psi_n(x,t) = \frac{N}{\sqrt{2^n\, n!}} H_n(Dx)\exp\{-i(n + \tfrac{1}{2})\cot^{-1}(\tfrac{\gamma}{2\omega} + \cot\omega t) - Ax^2\}, \tag{5}$$

where

$$N = \left(\frac{m\omega}{\pi\hbar}\right)^{\frac{1}{4}} \frac{e^{-\frac{1}{4}\gamma t}}{\zeta(t)\sin^{\frac{1}{2}}\omega t},$$

$$\zeta^2(t) = \frac{\gamma^2}{4\omega^2} + \frac{\gamma}{\omega}\cot\omega t + \operatorname{cosec}^2\omega t,$$

$$A(t) = \frac{m\omega}{2\hbar} e^{\gamma t}\left\{\frac{1}{\zeta(t)^2\sin^2\omega t} + i\left(\frac{\gamma}{2\omega} - \cot\omega t + \frac{\frac{\gamma}{2\omega} + \cot\omega t}{\zeta(t)^2\sin^2\omega t}\right)\right\},$$

$$D(t) = \left(\frac{m\omega}{\hbar}\right)^{\frac{1}{2}} \frac{e^{\frac{1}{2}\gamma t}}{\zeta(t)\sin\omega t}. \tag{6}$$

The quantum mechanical expectation values of mechanical energy E(Eq. (3)) take the form

$$< E >_{mn} = -\frac{\hbar^2}{2m} e^{-2\gamma t} < \frac{\partial^2}{\partial x^2} >_{mn} + \frac{1}{2} m\omega_0^2 < x^2 >_{mn}. \tag{7}$$

The evaluation of Eq. (7) gives the non-zero matrix elements which occur only in the principal diagonal and the two second off-diagonals:

$$< E >_{n+2,n} = [(n+2)(n+1)]^{\frac{1}{2}}\,\theta(t), \tag{8}$$

$$< E >_{nn} = \frac{1}{2}(n + \tfrac{1}{2})\hbar\omega\, e^{-\gamma t}\left[\frac{\omega_0^2}{\omega^2}\zeta(t)^2\sin^2\omega t + \frac{1}{\zeta(t)^2\sin^2\omega t}\right], \tag{9}$$

where

$$\theta(t) = \frac{1}{4}\hbar\omega e^{-\gamma t}\exp\Bigg\{[2i\cot^{-1}\left(\frac{\gamma}{2\omega} + \cot\omega t\right)][\zeta(t)^2\sin^2\omega t$$

$$- \frac{1}{\zeta(t)^2\sin^2\omega t} + \frac{1}{\zeta(t)^2\sin^2\omega t}\{(\frac{\gamma}{2\omega} - \cot\omega t)\zeta(t)^2\sin^2\omega t$$

$$+ \frac{\gamma}{2\omega} + \cot\omega t\}^2 - 2i\{(\frac{\gamma}{2\omega} - \cot\omega t)\zeta(t)^2\sin^2\omega t + \frac{\gamma}{2\omega}$$

$$+ \cot\omega t\}\,]\Bigg\}. \tag{10}$$

Taking the complex conjugate and changing n into (n-2) in Eq. (8) we can easily obtain the energy expectation value in (n-2, n) state.

In a similar way to that used to obtain Eq. (7) we can obtain the uncertainty relations in the various states:

$$[(\Delta p)(\Delta x)]_{n+2,n} = \frac{\hbar}{2}\{(n+2)(n+1)\}^{\frac{1}{2}}\beta(t), \tag{11}$$

$$[(\Delta p)(\Delta x)]_{n+1,n} = \frac{\hbar}{2}(n+1)\beta(t), \tag{12}$$

$$[\Delta p\cdot\Delta x]_{nn} = (n + \frac{1}{2})\hbar\beta(t), \tag{13}$$

and

$$\beta(t) = [1 + \{(\frac{1}{8}(\frac{\gamma}{\omega})^3 + (\frac{\gamma}{\omega}))\sin^2\omega t + \frac{1}{8}(\frac{\gamma}{\omega})^2\sin 2\omega t\}^2]^{\frac{1}{2}}. \tag{14}$$

Chainging n into (n-1) and (n-2) respectively in Eqs. (12) and (11) we can obtain the uncertainty relations in (n-1, n) and (n-2,n) states.

Before we construct the annihilation operator a and creation operator a^+, we give the properties of the coherent states. These ~~The coherent~~ states can be defined by the eigenstates of the nonhermitian operator a,

$$a|\alpha> \; = \; \alpha|\alpha> . \tag{15}$$

Using the completeness relation for the number representations, we can expand $|\alpha>$ as

$$\begin{aligned} |\alpha> &= e^{-\frac{1}{2}|\alpha|^2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} \, |n> \\ &= e^{-\frac{1}{2}|\alpha|^2} e^{\alpha a^+} \, |0> , \end{aligned} \tag{16}$$

where $|0>$ is the vacuum or ground state and is independent of n. The calculation of $<\beta|\alpha>$ in Eq. (16) gives

$$<\beta|\alpha> = e^{-\frac{1}{2}(|\alpha|^2+|\beta|^2)+\alpha\beta^*} . \tag{17}$$

Since Eq. (17) has nonzero value for $\alpha \neq \beta$, the states are not orthogonal, but when $|\alpha - \beta|^2 \rightarrow \infty$, the states become orthogonal.

The eigenvalues α of coherent states are complex numbers u + iv, and thus the completeness relation of coherent states is written as

$$\int |\alpha><\alpha|\frac{d^2\alpha}{\pi} = 1 , \tag{18}$$

where 1 is the identity operator and $d^2\alpha$ is given by $d(\mathrm{Re}\,u)d(\mathrm{Im}\,v)$.

To define a^+ and a for the damped harmonic oscillator we make use of Eq. (5) for $\langle x \rangle_{mn}$ and $\langle p \rangle_{mn}$:

$$\langle x \rangle_{mn} = \int_{-\infty}^{\infty} \psi_m^*(x)\, x\, \psi_n(x)\, dx$$

$$= \frac{1}{2}(n+1)^{1/2}(\mathrm{Re}A)^{-1/2}\exp\{i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)\}\,\delta_{m,n+1}$$

$$+ \frac{1}{2} n^{1/2}(\mathrm{Re}A)^{-1/2}\exp\{-i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)\}\,\delta_{m,n-1}$$

$$= (n + \frac{1}{2})^{1/2}\mu(t)\,\delta_{m,n+1} + n^{1/2}\mu(t)^*\,\delta_{m,n-1}, \tag{19}$$

$$\langle p \rangle_{mn} = \int_{-\infty}^{\infty} \psi_m^*(x)\,\frac{\hbar}{i}\frac{\partial}{\partial x}\psi_n(x)\, dx$$

$$= i\hbar\sqrt{2}(n+1)^{1/2}\frac{A}{D}\exp\{i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)\}\,\delta_{m,n+1}$$

$$+ i\hbar\sqrt{2}\, n^{1/2}(\frac{A}{D} - D)\exp\{-i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)\}\,\delta_{m,n-1}$$

$$= (n + \frac{1}{2})^{1/2}\eta(t)\,\delta_{m,n+1} + n^{1/2}\eta^*(t)\,\delta_{m,n-1}, \tag{20}$$

where

$$\mu(t) = \frac{1}{2}(\mathrm{Re}A)^{-1/2}\exp[i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)], \tag{21}$$

$$\eta(t) = \sqrt{2}\, i\hbar\frac{A}{D}\exp[i\cot^{-1}(\frac{\gamma}{2\omega} + \cot\omega t)], \tag{22}$$

and we have the relation

$$\eta\mu^* - \eta^*\mu = 2i \ \mathrm{Im}\{ \frac{1}{2} (\mathrm{Re}A)^{+\frac{1}{2}} \sqrt{2}\, i\hbar \frac{A}{D} \} = i\hbar . \tag{23}$$

Therefore, we define the annihilation operator a and creation operator a^+ for the damped harmonic oscillator as ~~follows~~

$$a = \frac{1}{i\hbar} (\eta x - \mu p), \tag{24}$$

$$a^+ = \frac{1}{i\hbar} (\mu^* p - \eta^* x), \tag{25}$$

where the expressions of x and p by a and a^+ are

$$x = \mu^* a + \mu a^+, \tag{26}$$

$$p = \eta^* a + \eta a^+. \tag{27}$$

Since η is not equal to μ in Eqs. (21) - (22), we can easily conform that a and a^+ are not hermitian operators, but the following relations are preserved:

$$[\ x,p\ ] = i\hbar \tag{28}$$

$$[\ a,a^+\ ] = 1 . \tag{29}$$

Now we evaluate the transformation function $< x|\alpha >$ from coherent states to the coordinate representation $|x>$. From Eqs. (15) and (24)

we have

$$(\eta x' - \mu \frac{\hbar}{i} \frac{\partial}{\partial x'}) < x'|\alpha > = i\hbar\alpha < x'|\alpha > . \tag{30}$$

For convenience we change the variable x' into x and solve this differential equation, to obtain ~~and we get~~

$$< x|\alpha > = N \exp\{\frac{1}{\mu} \alpha x - (2 i \hbar \mu)^{-1} \eta x^2 \} , \tag{31}$$

where N is the integral constant. Taking N to satisfy Ey. (18), we find ~~obtain~~ the eigenvectors of the operator a given in the coordinate representation $|x>$:

$$< x|\alpha > = (2\pi\mu\mu^*)^{-\frac{1}{4}} \exp\{- \frac{1}{2i\hbar} \frac{\eta}{\mu} x^2 + \frac{\alpha}{\mu} x - \frac{1}{2} |\alpha|^2 - \frac{1}{2} \frac{\mu^*}{\mu} \alpha^2 \} . \tag{32}$$

Next we show that a coherent state represents a minimum uncertainty state. With the help of the relations between a, a^+, x and p we evaluate the expectation values of x, p, x^2 and p^2 in state $|\alpha>$:

$$\begin{aligned} < x > &= < \alpha|\mu^* a + \mu a^+|\alpha > = \mu^*\alpha + \mu\alpha^*, \\ < p > &= < \alpha|\eta^* a + \eta a^+|\alpha > = \eta^*\alpha + \eta\alpha^*, \\ < x^2 > &= \mu^{*2}\alpha^2 + \mu\mu^*(1 + 2\alpha\alpha^*) + \mu^2\alpha^{*2}, \\ < p^2 > &= \eta^{*2}\alpha^2 + \eta\eta^*(1 + 2\alpha\alpha^*) + \eta^2\alpha^{*2}. \end{aligned} \tag{33}$$

From Eq. (33) we have

$$(\Delta x)^2 = < x^2 > - < x >^2 = \mu\mu^*, \tag{34}$$

$$(\Delta p)^2 = < p^2 > - < p >^2 = \eta\eta^*, \tag{35}$$

and thus the uncertainty relation becomes

$$(\Delta x)(\Delta p) = \{|\eta|^2|\mu|^2\}^{\frac{1}{2}} = \frac{\hbar}{2}\ \beta\,(t). \tag{36}$$

Eq. (36) is the minimum uncertainty corresponding to Eq. (13) in (0,0) state.

All of the formulas, we have derived, are reduced to those of simple harmonic oscillator when $\gamma = 0$. The propagator (Eq. (4)) has very similar form to those of Cheng[15] and others,[17] but the wave function (Eq. (5)) is of new form.

We should note that the same classical equation of motion can be obtained from many different actions, and thus one may have many different propagators corresponding to the actions. Therefore it is very important to get the correct propagator. The mechanical energy (Eq. (3)) is not identical to the Hamiltonian operator (Eq. (1)). Hence ~~Therefore~~ we assume that this Hamiltonian represents the quantum mechanical dissipative system.

Figures ~~Fig.~~ 1 and 2 illustrate the decay of the energy expectation value and the uncertainty relation as a function of γ/ω in (n, n) state. Although ~~As though~~ we have shown only the principal diagonal element, i.e., $< E >_{nn}$ of the energy expectation values, there are four off-diagonals adjacent to the principal diagonal, which are involved in the exponential decaying term

$e^{-\gamma t}$. $< E >_{nn}$ approaches the constant value as $\frac{\gamma}{\omega} \to 0$. The uncertainty for the (n, n) state with period π (Eq. (13)) is reduced to that of the harmonic oscillator at 0° and 180°.

From all of the above we conclude that the coherent states for the damped harmonic oscillator, with the Caldirola-Kanai Himiltonian we have constructed, satisfy the properties of coherent states (1)-(4).

Acknowledgements

We are ~~I am~~ grateful to Professor S. W. Kim for helpful comments. This research was supported partly by Korea University and by the office of Naval Research, the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009. and the National Science Foundation under Grant CHE-8620274.

Figure Caption

Fig. 1. Energy expectation value for (n, n) state as a function of ωt at the various value of γ/ω. As γ/ω tends to zero, the energy approaches the constant values.

Fig. 2. Uncertainty relation for the (n, n) state versus ωt at various values of γ/ω .

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Fig. 1

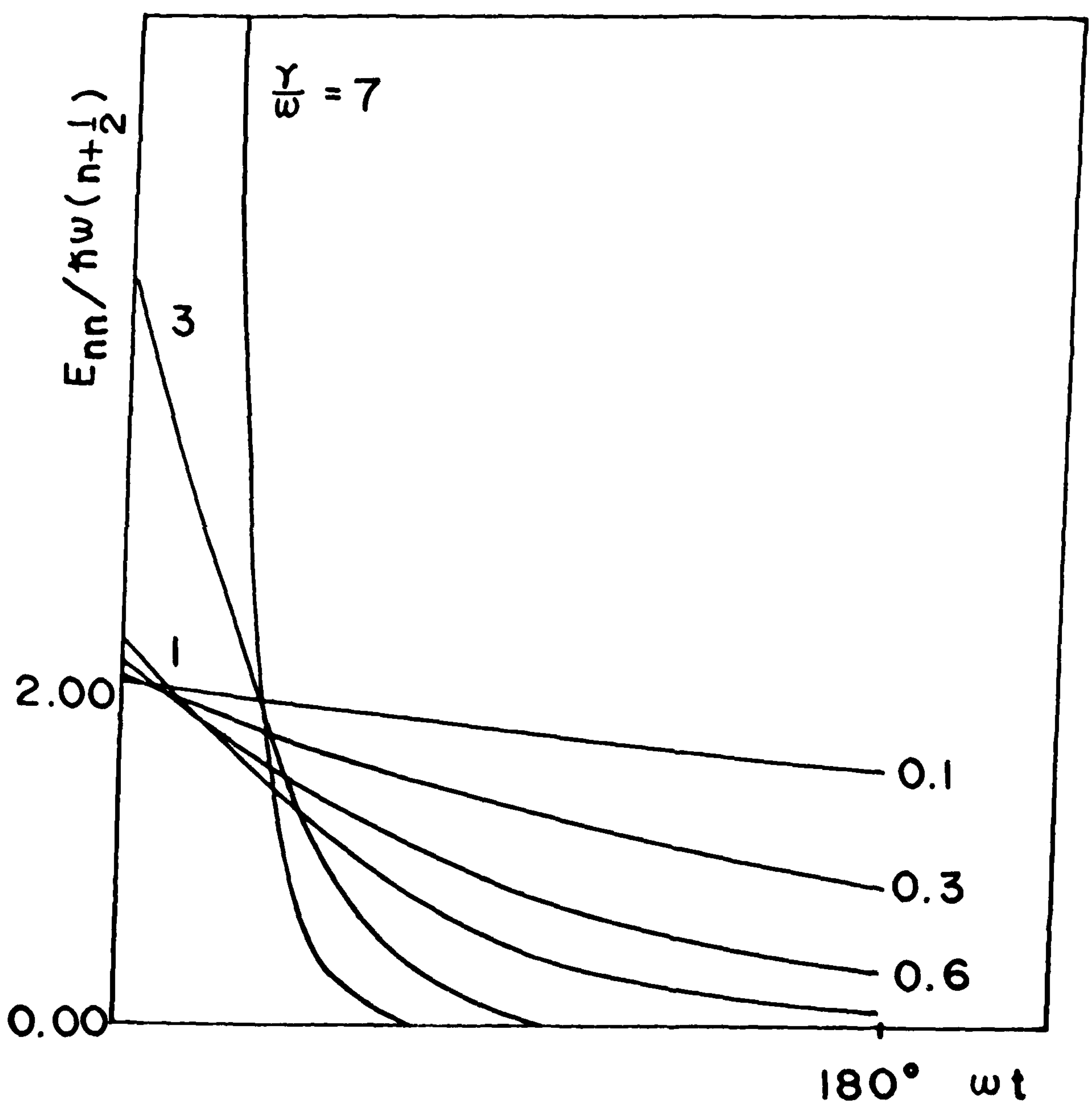

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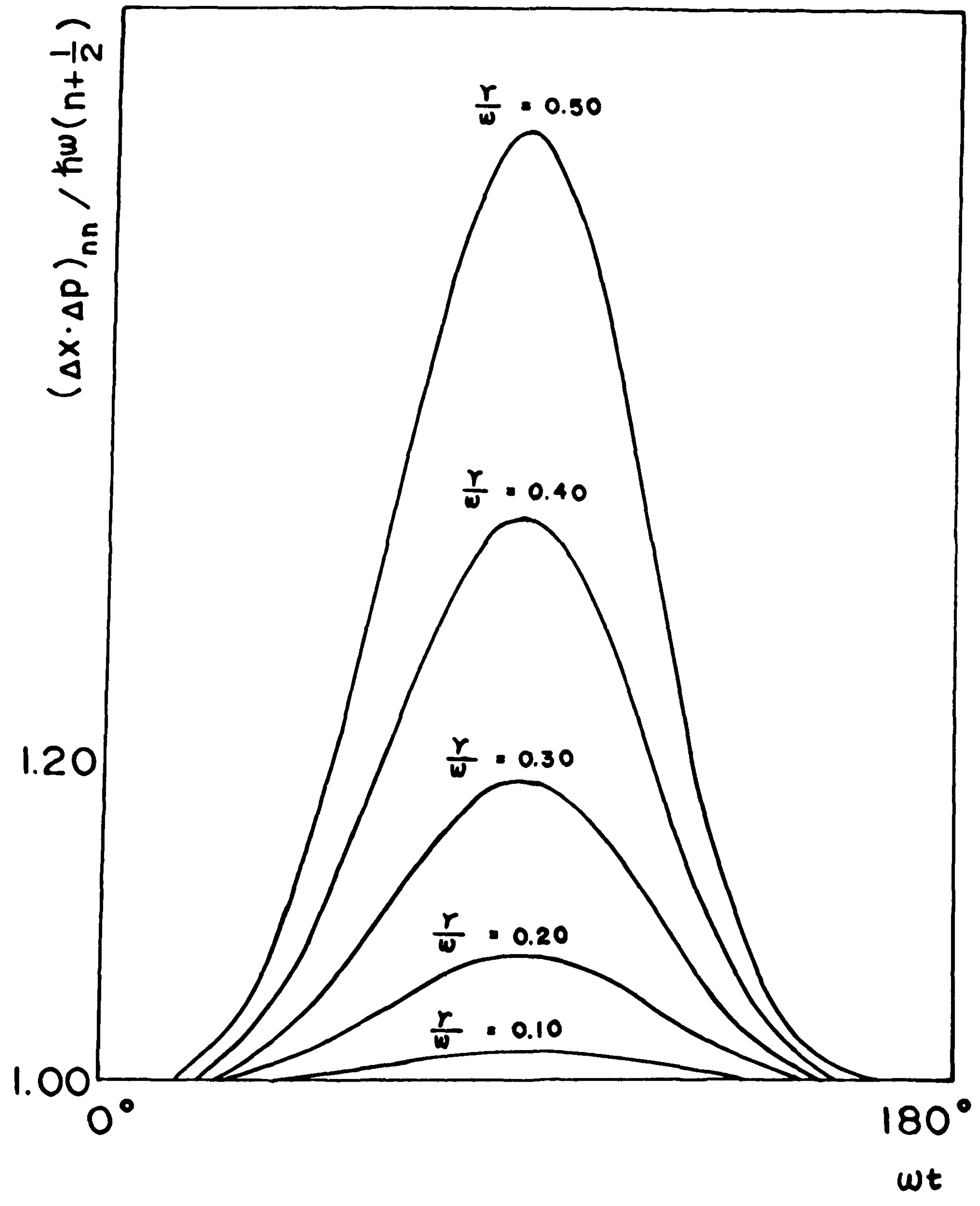
Fig. 2



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